The Jenolan Environmental Monitoring Program

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The Jenolan Environmental Monitoring Program reports on the condition of atmospheric and water parameters in and around the show caves at Jenolan. This paper summarises the key findings from four years (2009-2012) of monitoring cave atmosphere. The caves were typically characterised by high relative humidity, moderately stable air temperature (annual variation <2°C) and pronounced seasonal variation in the concentration of CO_2. A major exception was the Temple of Baal, where CO_2 was moderately elevated (~2,000 ppm) year round, with no apparent seasonal variation. The concentrations of CO_2 in the caves were generally well below the exposure limit and pose minimal risk to human health.

Abrupt increases in air temperature of up to 0.9°C in <12 minutes occurred in several of the caves, in particular the Imperial. These increases were characteristic of, and generally corresponded to, commercial tours, and rapidly stabilised back to the pre-tour temperature after the tour had passed. Similarly, increases in CO_2 associated with visitation were generally short lived, except in the Temple of Baal, where peak visitation elevated the CO_2 for extended periods of time. The merits and shortfalls of various options for managing the accumulation of CO_2 in the Temple of Baal are discussed.

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KEYWORDS: carbon dioxide, cave atmosphere; Jenolan Caves, temperature, tourist cave.

INTRODUCTION

The maintenance of natural processes within karst environments is highly dependant on the interactions between the soil, water and air (Watson et al. 1997). In recognition of these interactions, karst managers around the world are increasingly utilising air and water monitoring programs to examine the impacts of humans in show caves (e.g. Pulido-Bosch et al. 1997; Russell and MacLean 2008; Lario and Soler 2010). Indeed Cigna (2004) recommends that the atmosphere in all show caves should be monitored to determine whether cave operations are having adverse impacts on these unique and delicate environments.

Jenolan Caves are arguably Australia's best known show caves, attracting more than 200,000 visitors each year (Jenolan Caves Reserve Trust 2012). In 2004 the Jenolan Caves Reserve Trust (JCRT) received $4.2 million to undertake capital works within Jenolan Karst Conservation Reserve (JKCR). Of this funding, approximately $200,000 was allocated to the development of an air and water quality monitoring program. Sites for air and water monitoring and equipment were selected in 2006 in consultation with the Jenolan Scientific and Environmental Advisory Committee, with monitoring equipment purchased in 2007 and progressively installed in 2008-2009.

The Jenolan Environmental Monitoring Program (JEMP) measures air and water quality parameters that are of relevance to karst conservation, the maintenance of biological diversity and visitor safety. The measurement and reporting of such parameters enables an objective evaluation of the environmental performance of JCRT (or any future successor), with regards to air and water quality in the show caves. Specifically, the JEMP aims to achieve this by establishing and reporting trends in air quality and the relationship between these trends and anthropogenic activity (in particular commercial cave tours) and trends in water quality at a number of sites with the catchment of the tourist caves. This paper presents the key findings from four years (2009-2012) of monitoring cave atmosphere in the show caves at Jenolan.

METHODS

Sites

The Jenolan Karst Conservation Reserve (JKCR), is located approximately 180 km southwest of Sydney (33°49'S, 150° 02'E) and one of eight reserves that comprise the Greater Blue Mountains World Heritage Area (DECC 2009). Monitoring of cave atmosphere was conducted at seven sites within the show caves and one external reference site. Three monitoring sites were situated in the Northern Show Caves (Chifley, Diamond and Imperial) and four sites in the Southern Show Caves (Mafeking Branch of Lucas, Orient, River and Temple of Baal (Fig. 1, Table 1).

Equipment

Commercially available instruments manufactured by Vaisala were utilised to measure air temperature (Vaisala 'HMT 100', ± 0.2°C), relative humidity (Vaisala 'HMT 100', ±2.5% RH), barometric pressure (Vaisala 'PTB 110' ±0.3 hPa) and the concentration of carbon dioxide (CO_2) (Vaisala 'GM220' ±1.5% of range + 2 % of reading) at each monitoring site. Monitoring equipment was housed within a sealed case at each site and connected to the cave power supply. A data logger (ACR Systems Inc. 'SmartReader Plus 7') recorded each of the parameters every 6 minutes. This interval was chosen following preliminary trials in 2008, which found 6 minute intervals were a sufficient frequency to capture the influence of passing tour groups, whilst providing sufficient storage time (2 months 12 days) before the logger began to rewrite over the oldest data. Data were downloaded every 2 months for analysis and inclusion in bi-monthly Condition Reports that are provided to the JCRT by the OEH Karst and Geodiversity Unit.

Data analysis

Data were filtered using the 'macro' and 'IF' functions in Microsoft Excel to remove data that exceeded a maximum permissible temperature range between the temperature probe and the data logger (≤8°C) or maximum permissible change between two consecutive time internals (≤2°C change in six minutes). These values were determined from the results of preliminary trails in 2008, which ascertained the largest genuine difference between the temperature probe and the data logger (i.e. the

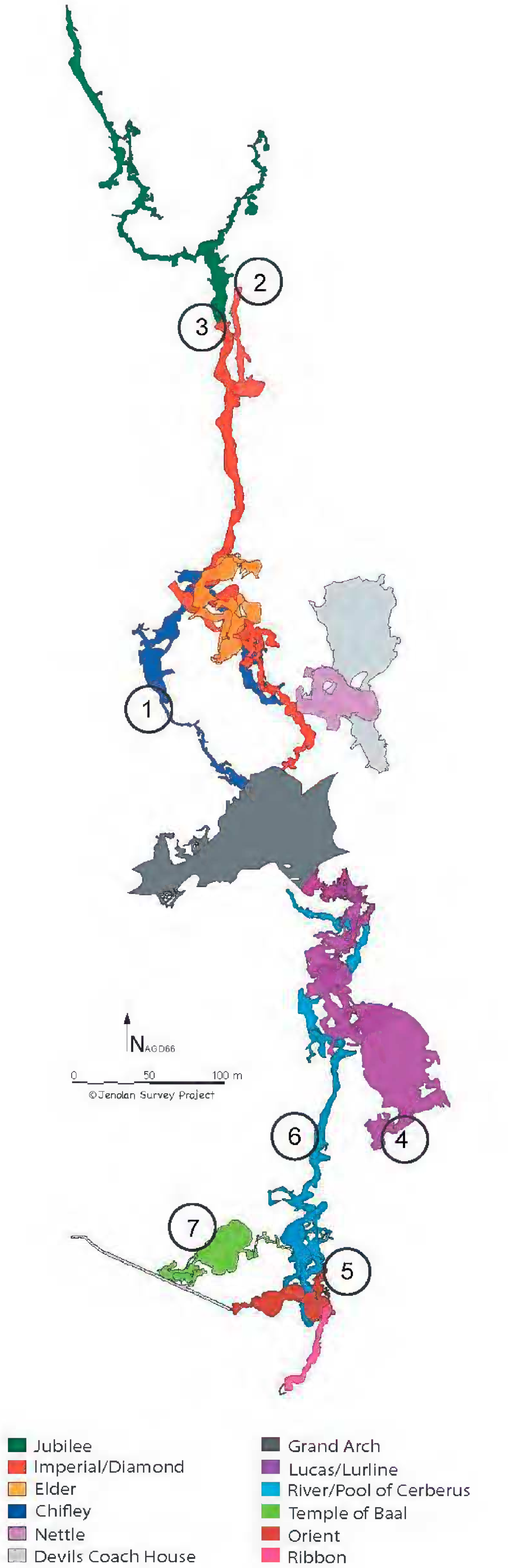


Figure 1. Map of the tourist cave system at Jenolan. Monitoring sites are numbered as per the description in Table 1. Image courtesy of the Jenolan Survey Project.

Table 1. Air monitoring sites

Name	Site number	Site description
Northern Show Caves		
Chifley Cave	1	In Katie's Bower, on the tourist platform above the mains power distribution
Diamond Cave	2	Approximately 5 m beyond the end of the public viewing area.
Imperial Cave	3	Nellie's Grotto
Southern Show Caves		
Lucas Cave	4	In the Mafeking branch approximately ten steps below the highest point of elevation
Orient Cave	5	In Lower Indian Chamber
River Cave	6	Under the bridge approximately 15 m before the Pool of Reflections
Temple of Baal	7	At the middle junction next to the switchboard
External site		
School House	8	On the south facing wall.

temperature in the sealed case), and largest change between consecutive temperature readings. Filtering the data was necessary to remove false values that occurred as a result of power outages and surges. Where temperature values at a site were false, it was assumed that all other parameters at that point in time were also false. The final step of filtering the data involved manually checking the graphed data for anomalies. For example, it was common for several sites to simultaneously experience an abrupt decrease of all parameters and such values were regarded as false and removed from the dataset.

Bimonthly datasheets were combined into a single spread sheet to determine the average, maximum and minimum values for each of the parameters for the four year period. The daily average air temperature, relative humidity and CO_2 were calculated for each day from January 1, 2009 to December 31, 2012 and graphed to examine any variation in cave atmosphere between seasons from one year to the next. Lastly, to ascertain the influence of commercial cave tours on the cave atmosphere, air temperature, relative humidity and CO_2 data, one week of continuous data (i.e. readings taken every six minutes) for April 5-11 2012 was graphed at a larger scale. This period was chosen as it included Easter (April 6-8), typically one of the busiest periods of visitation during the year.

RESULTS

Overview of cave atmosphere

The average air temperature in the caves ranged from 11.7°C in the Diamond Cave to 15.5°C in the Temple of Baal (Table 2, Fig. 2a). In comparison to the external site, where the average air temperature was 12°C and ranged from -4°C in winter to > 30°C summer, the air temperature within the caves was highly stable. The Temple of Baal had the least variation, with a temperature range of 0.6°C, while the Chifley experienced the largest range (3.2°C, Fig. 2a). Similarly for relative humidity (RH), while the external site experienced a highly degree of variability (6.9 - 99.6 % RH), the cave atmosphere was characterised by very high (98.8 - 99.9 %) and stable RH (Table 2, Fig. 2b). As with air temperature, the Chifley experienced the largest range in RH (9.7 %). However given the low variability of RH compared to the precision of the probes (± 2.5%), detailed analysis was not possible.

Whereas the caves experienced considerably less variation in air temperature and RH than the external site, this was not the case for CO_2, with the cave atmosphere recording a much larger range in CO_2 than the external atmosphere (Fig 2c). In comparison to the external atmosphere (~380 ppm) the average concentration of CO_2 at the monitoring sites within

Table 2. Average data (2009-2012) for air temperature, relative humidity and the concentration of CO_2 at each of the monitoring sites.

	Chifley	Diamond	Imperial	Lucas	Orient	River	Temple of Baal	External
Temperature (°C)								
Mean	12.98	12.65	13.04	14.24	14.94	13.36	15.49	12.01
SD	0.33	0.09	0.11	0.06	0.11	0.20	0.05	7.13
Range	3.22	1.02	1.57	2.03	0.94	1.66	0.63	-
Relative humidity (%)								
Mean	98.75	99.74	99.85	99.69	99.12	99.61	99.47	72.63
SD	0.59	0.17	0.10	0.01	0.31	0.31	0.06	18.61
Range	9.72	4.37	3.91	2.73	3.79	4.48	1.89	92.74
CO_2 (ppm)								
Mean	1,013.4	848.0	857.2	1,098.8	759.2	718.6	2,142.1	381.4
SD	853.1	275.6	413.5	461.3	347.1	333.4	425.3	35.2
Range	4,847.9	1,596.6	2,333.3	2,022.2	2,292.3	1,668.4	2,690.6	352.1

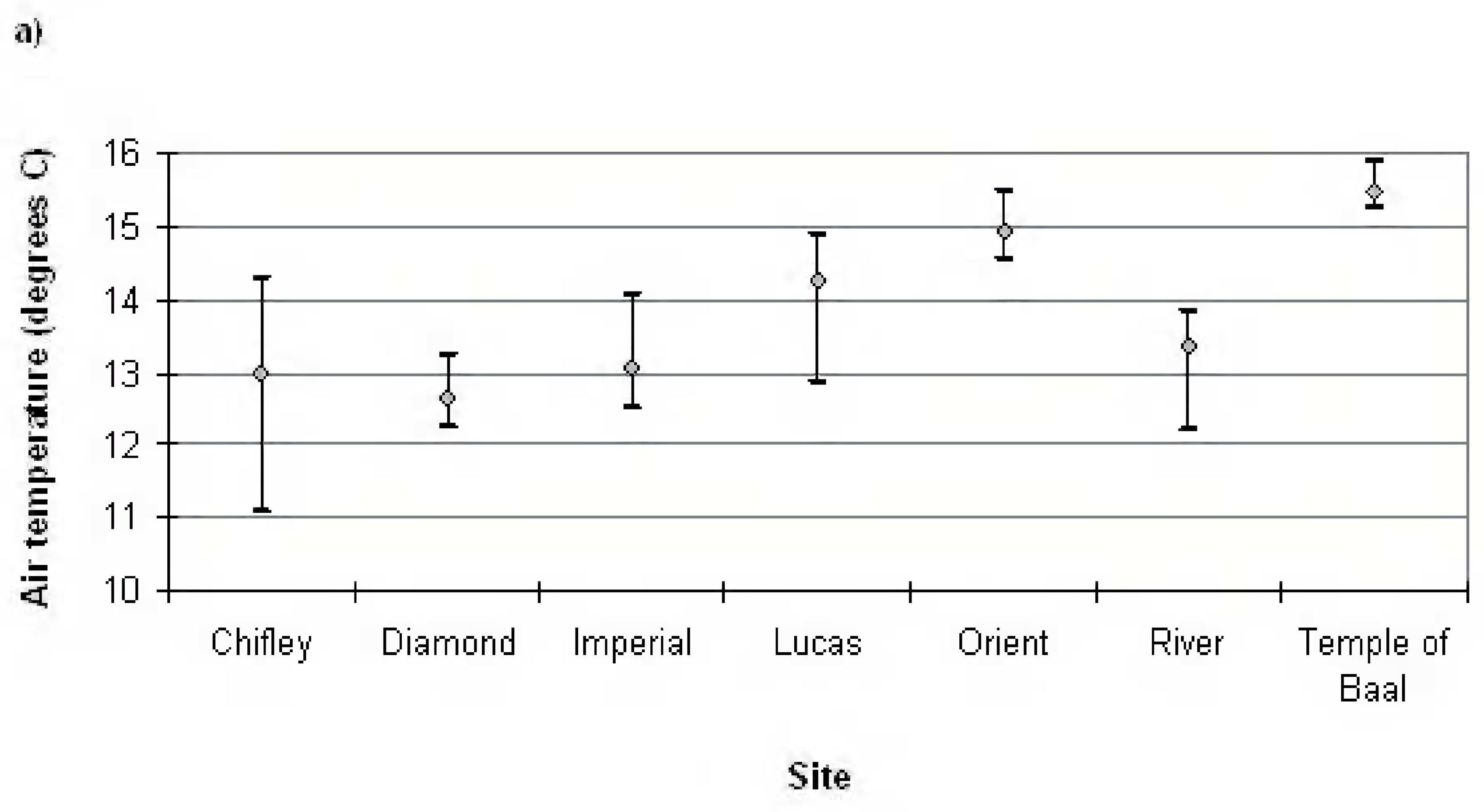
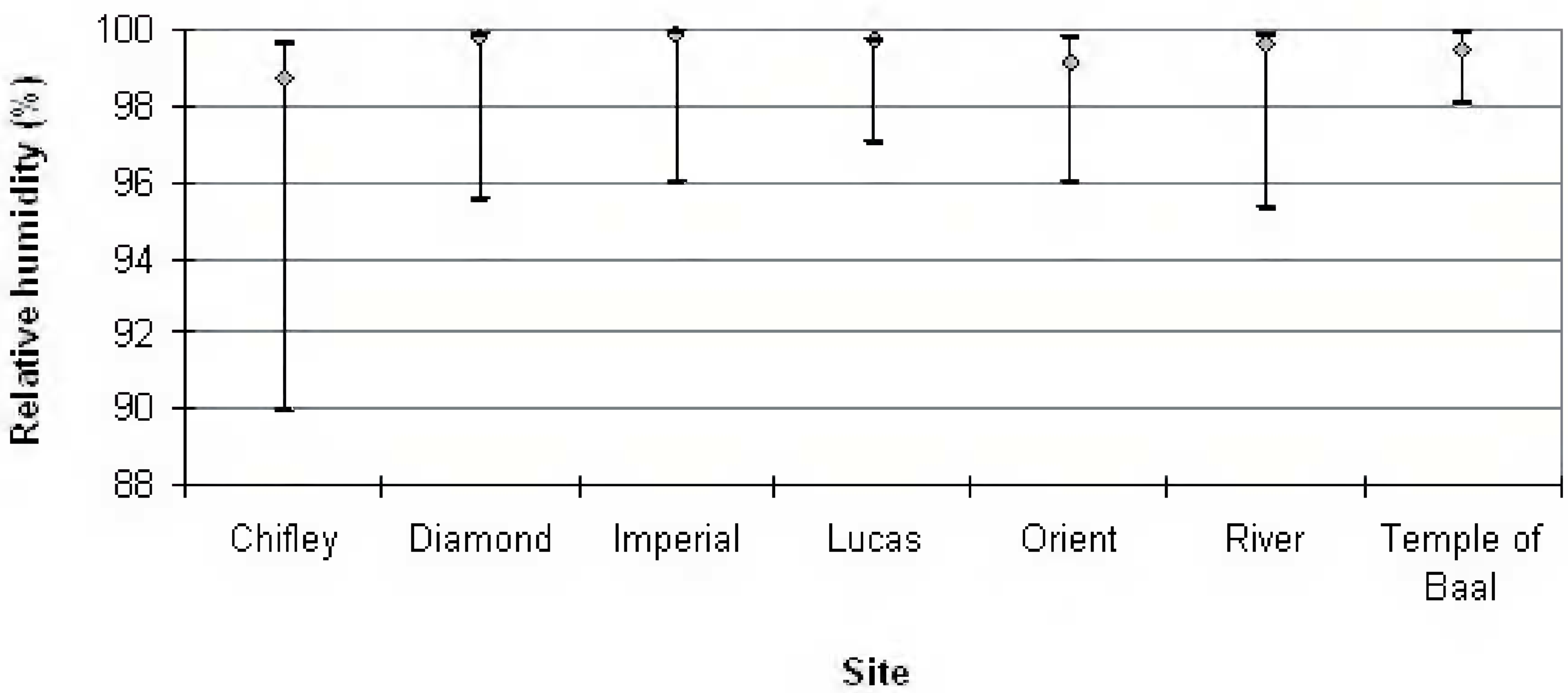


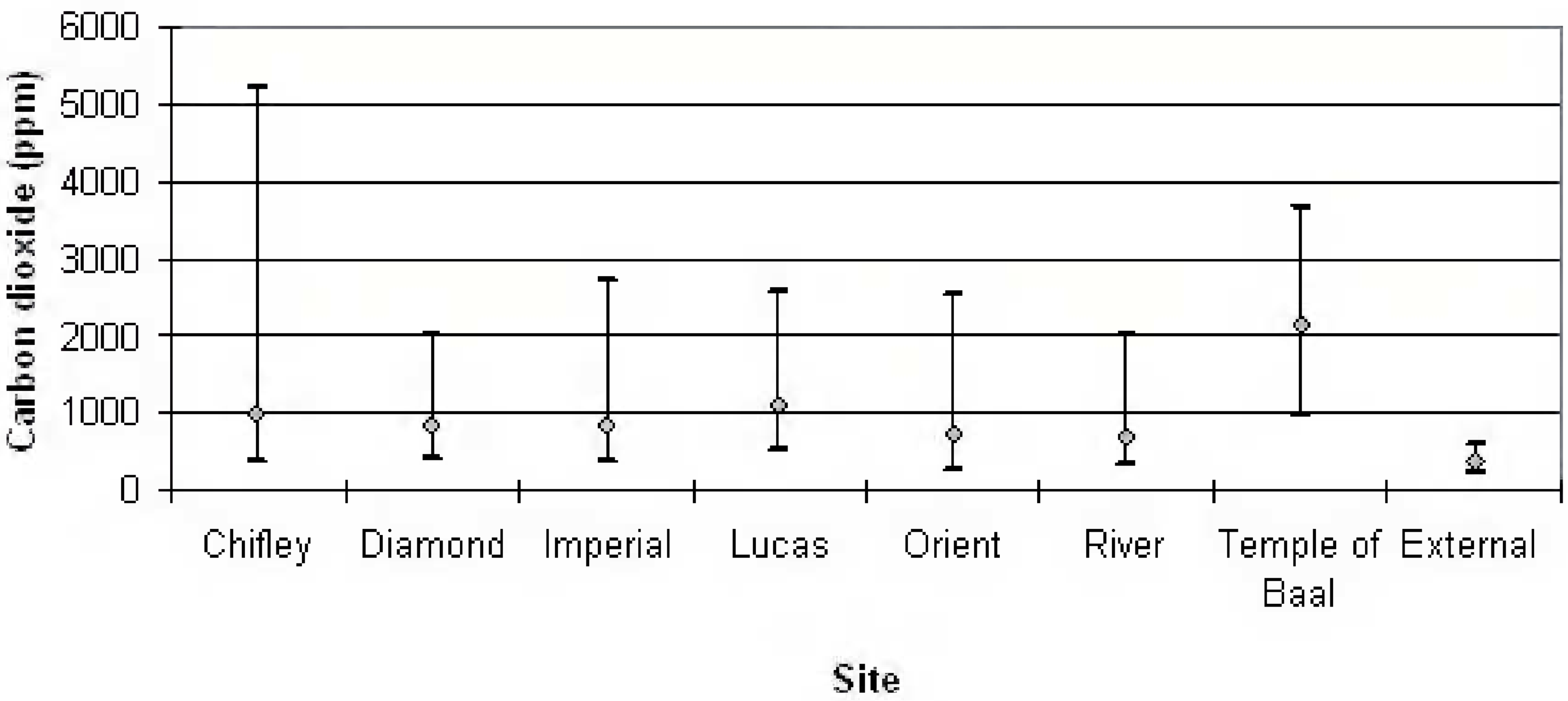
Figure 2. Average a) air temperature, b) relative humidity (RH) and c) CO_2 concentration at each of the monitoring sites from January 1 2009 to December 31 2012. The high-low lines show the range (maximum and minimum values). Temperature and RH data for the external site are not shown due to the high degree of variability. [b) and c) on following page].

Figure 2 continued

b)



c)



the caves ranged from 848 ppm in the Diamond to 2,142 ppm in the Temple of Baal. While the average concentration of CO_2 was markedly higher in Temple of Baal compared with the other caves, the highest concentration of CO_2 occurred in the Chifley (5,232 ppm). With the exception of the Chifley and Temple of Baal (maximum CO_2 = 3,662 ppm), the maximum concentration of CO_2 that occurred at any of the other sites within the caves was < 3,000 ppm (Fig. 2c).

Trends in cave atmosphere through time

Seasonal variation in the average daily air temperature was most pronounced in the Chifley and River caves, with the difference in the average air temperature between summer and winter of 0.8-1.2°C in the Chifley and 0.6-0.7°C in the River Cave (Fig. 3). In the River Cave, the minimum air temperature typically did not occur until the end of winter (mid-late August), whereas in the Chifley, the minimum air temperature occurred much earlier in winter. Seasonal variation in the Imperial was inconsistent, with the difference between summer and winter average air temperature ranging from ~0.4°C in 2009 to ~0.1°C 2012 (Fig. 3). Unfortunately the temperature-relative humidity unit in the Temple of Baal and data logger in the Orient required repair on several occasions.

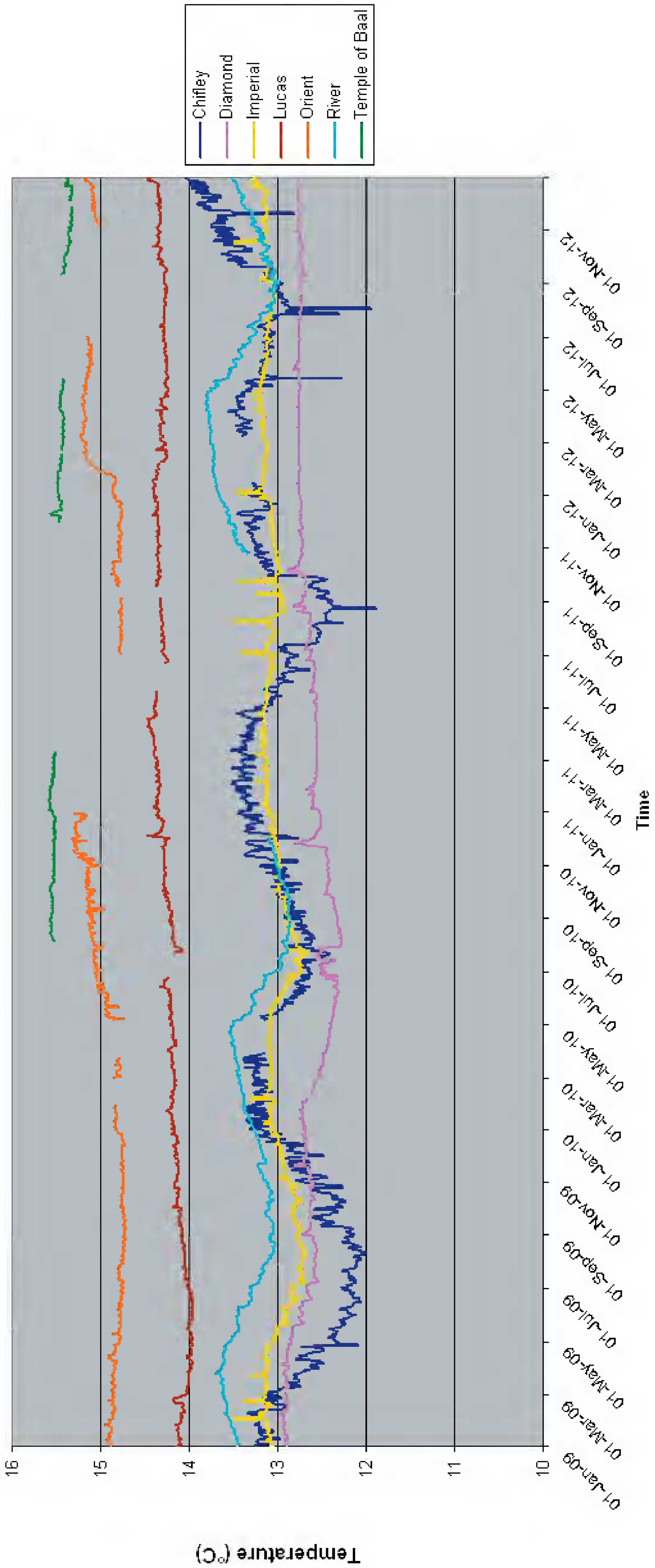


Figure 3. Average daily air temperature at each of the monitoring sites within the caves.

Consequently there are substantial gaps in the data for both these caves, although the data suggest these sites are characterised by generally highly stable air temperatures.

With the exception of the Temple of Baal, the concentration of CO_2 in the caves varied between seasons. CO_2 peaked during the summer months (December-January), decreased during autumn, was at a minimum during winter (June-August) and increased again in spring and summer (Fig. 4). During summer, the maximum average concentration of CO_2 in the caves was approximately 4-10 times that of the external site, whereas in winter, the CO_2 in the caves (excluding the Temple of Baal) was often only slightly elevated above the external atmosphere, with a maximum concentration 1.5-2 times that of the external atmosphere. CO_2 in the Temple of Baal showed no relationship with season, with major increases typically occurring during periods of peak visitation, as discussed in the following section.

Influence of visitors on cave atmosphere

Abrupt increases or "spikes" in air temperature occurred in several caves and were most pronounced in the Imperial, Lucas and Orient (Fig. 5a). Of these caves, the Imperial experienced the largest spikes in air temperature, with increases of up to 0.59°C in < 12 minutes during Easter 2012 (Fig. 5a). Increases of 0.5-0.7°C frequently occurred in the Imperial throughout the four years of monitoring (as noted in the Bimonthly reports prepared for JCRT), and this cave consistently recorded the largest spikes in air temperature. The largest single spike in air temperature, an increase of 0.9°C, occurred on the 10th March 2012. Spikes of between 0.2-0.5°C were typical in the Lucas Cave, as was evident during Easter 2012. Although spikes in the Orient were often smaller than those in the Imperial and Lucas (typically ~0.2°C), they generally occurred on a more frequent and regular basis (Fig. 5a). It is important to note that tours in the Imperial and Lucas frequently did not longer enter the sections of the caves containing monitoring sites, whereas every tour that entered the Orient entered the chamber where monitoring was conducted.

With the exception of the Chifley Cave, the RH in the other caves remained virtually constant throughout the week, irrespective of commercial tours (Fig 5b). In the Chifley Cave, RH, like air temperature was highly variable and typically increased when air temperature within the cave decreased, and decreased when air temperature increased.

The concentration of CO_2 in cave atmosphere generally increased midmorning each day, coinciding with the commencement of cave tours. Increased visitation over the Easter period had a pronounced influence on the concentration of CO_2 (Fig. 5c). On Thursday 5th April, most of the caves recorded only small increases in CO_2, in keeping with relatively low rates of visitation. Conversely over Easter, significantly increases in visitation led to higher concentrations of CO_2 for periods of time. For example in the Lucas Cave, an increase in visitation of between 500-1,000 people/day during April 6-8 resulted in substantially larger increases in CO_2 than April 5 (Fig. 5c), when only 140 people visited the cave.

Different caves experienced different trends in the accumulation of CO_2. As with air temperature, abrupt spikes in CO_2 occurred in the Imperial, Lucas and the Orient (Fig. 5c). These abrupt increases were usually relatively short-lived, however when tours were frequent, the concentration of CO_2 did not decrease to the pre-tour level before the next tour. This frequently resulted in elevated levels of CO_2 until there was a substantial gap between tours or after the last tour for the day. In the River Cave, CO_2 accumulation was more gradual, increasing mid-late morning and decreasing each evening (Fig. 5c).

Interestingly, the Temple of Baal exhibited very different trends in CO_2 compared to the other caves. During periods of increased visitation such as Easter 2012, the level of CO_2 in the Temple of Baal gradually increased with visitation during the day, plateaued or marginally decreased during the evening and until the commencement of tours the following day (Fig. 5c). Conversely on days when there were fewer visitors, such as April 5, 2012, there was a slight decrease in the average concentration of CO_2. Indeed throughout 2009-2012, periods of high visitation consistently resulted in peak levels of CO_2 (Fig. 6).

To examine the relationship between visitation, air temperature and CO_2 concentrations, these parameters were graphed side by side for the Orient Cave (Fig. 7). Simultaneous spikes in air temperature and CO_2 corresponded with each and every one of the tours through the cave. As could be expected, the size of each tour influenced the magnitude of the spikes in air temperature and CO_2. For example on April 5, four similar sized tours during the day resulted in four comparable spikes in air temperature and CO_2, while a smaller 8 pm "extended Orient" tour resulted in much smaller spikes in temperature and CO_2. During the Easter long weekend (April 6-9 2012), the frequency of tours was such that after a tour, the air temperature and CO_2 to did not decrease to the pre-tour level before the next tour, resulting in a period where temperature and CO_2 were elevated (Fig. 7).

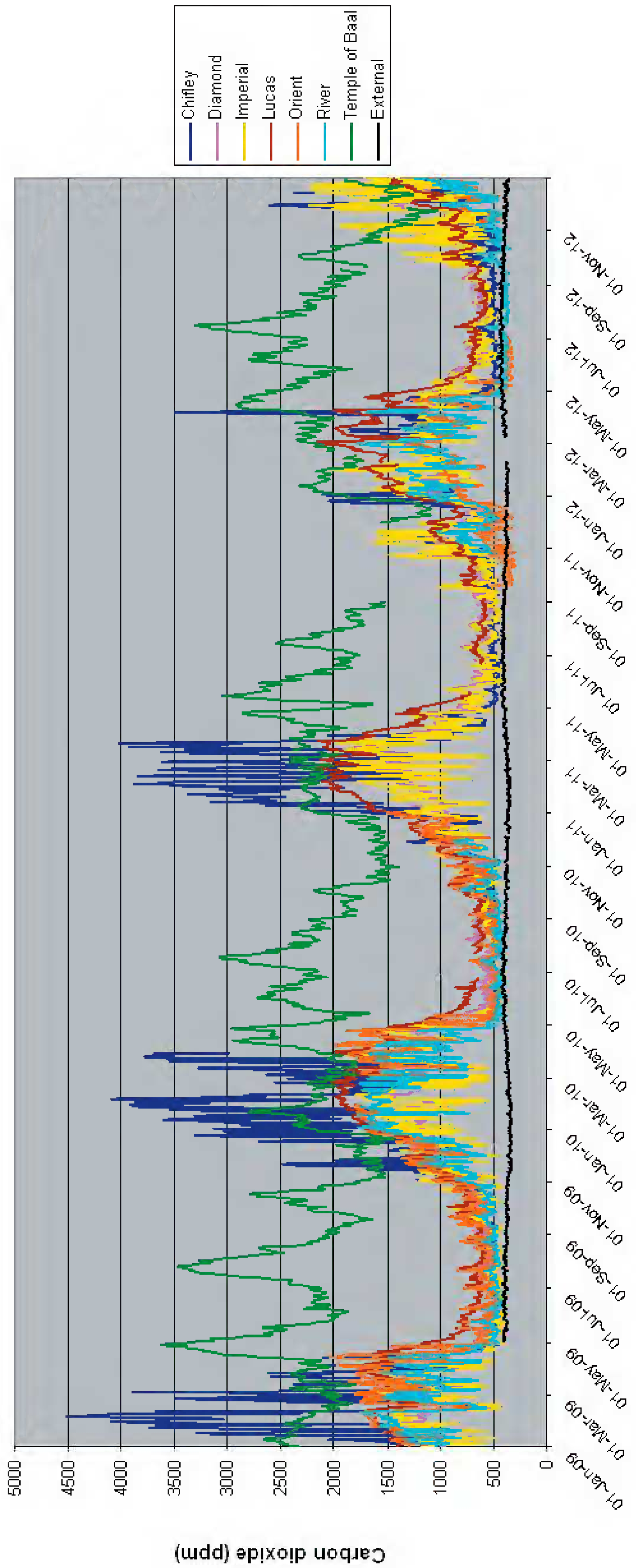


Figure 4. Average daily concentration of carbon dioxide at each of the monitoring sites.

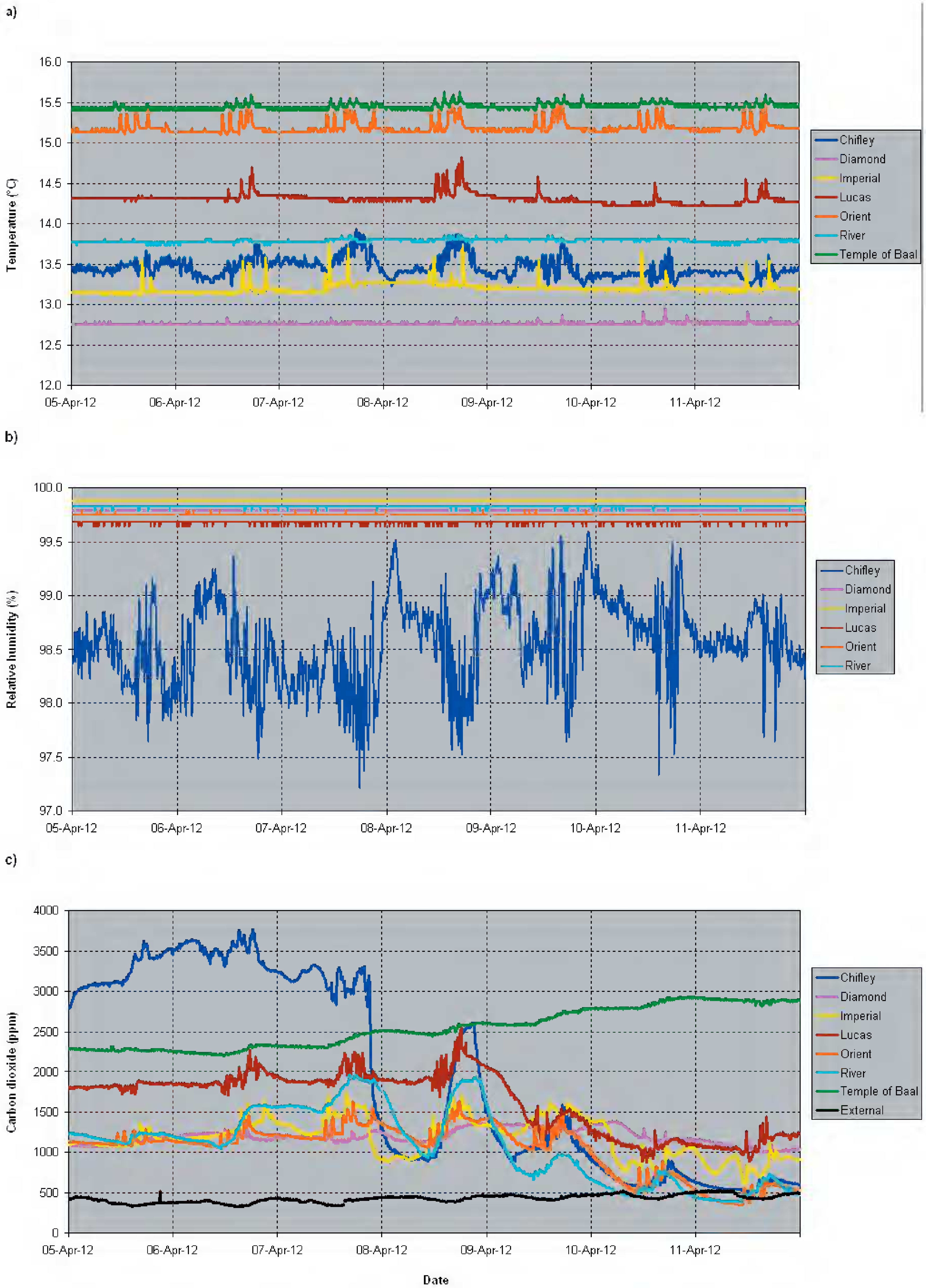


Figure 5. Daily variation in a) air temperature, b) relative humidity (RH) and c) CO_2 concentration at each of the monitoring sites from April 5 to 11 2012. Each parameter was recorded at 6 minutes intervals.

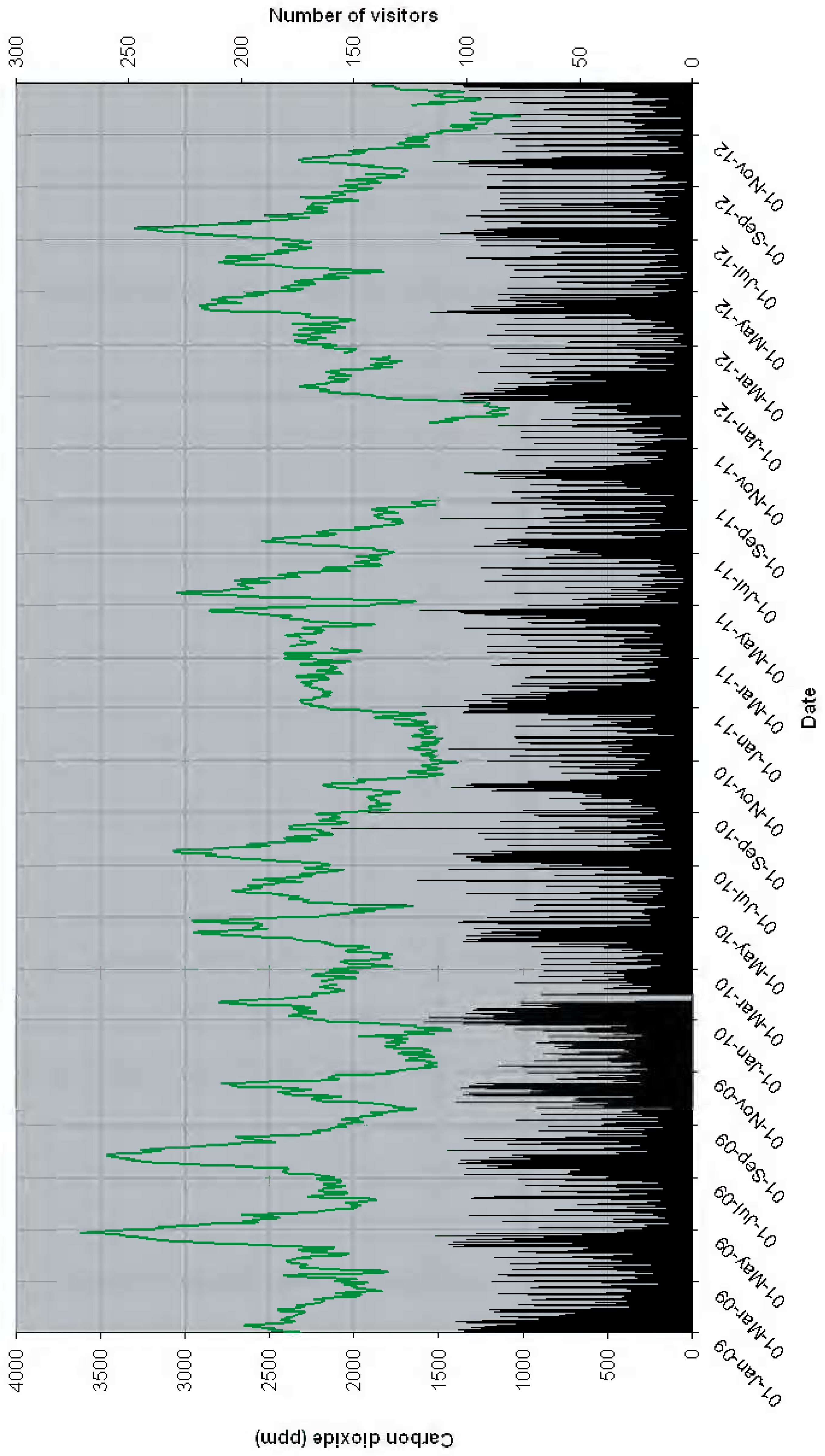


Figure 6. Relationship between the concentration of carbon dioxide in the Temple of Baal and number of visitors to the cave each day. Note: no visitor data were available for March 23-29 2010.

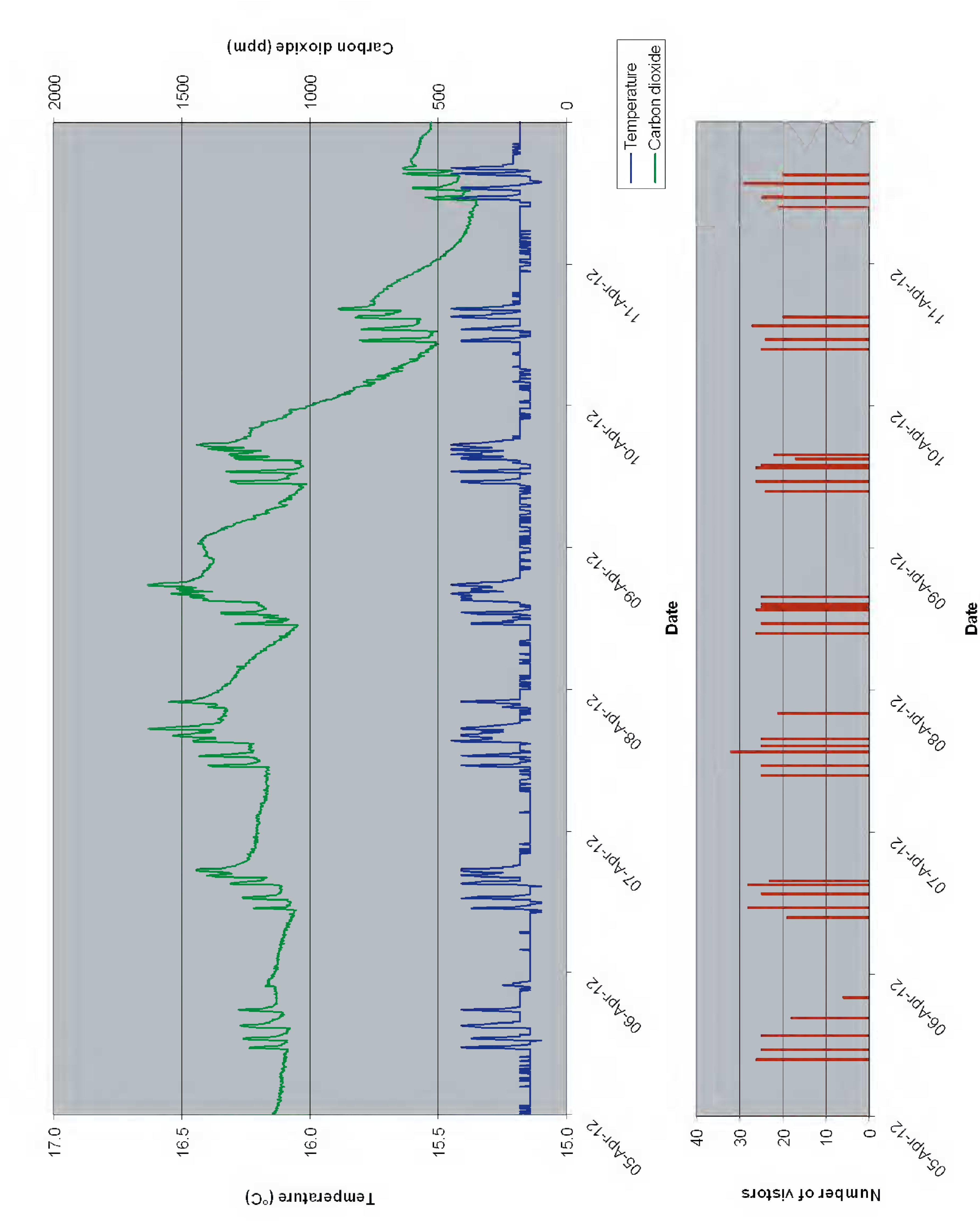


Figure 7. Relationship between commercial tour groups, air temperature and CO_2 concentration in the Orient.

DISCUSSION

Trends in cave atmosphere

Of all the caves, the Chifley had the most variable atmosphere, and experienced considerable day to day variation and pronounced seasonal trends in air temperature and CO_2. These trends are consistent with strong ventilation in the cave (Whittlestone et al. 2003) and current research by Waring and Hankin (2013), which has shown the occurrence of bi-directional airflow and daily cycles of ventilation through the upper (i.e. the Elder / Plug Hole) and lower entrances to the cave. Conversely, the most stable air temperature occurred in the Temple of Baal, a cave known to have limited ventilation (Whittlestone et al. 2003). As with air temperature, strong ventilation in the Chifley Cave accounts for greater variability of RH in the Chifley compared to the other caves.

The average (2009-2012) air temperature differed by up to 2.8°C between the sites within the caves. These differences were predominately attributed to the location of individual caves within the larger cave system. For example the warmest caves were the Temple of Baal, the Orient and Mafeking branch of the Lucas Cave, all of which are situated in the upper levels of the southern show caves, while the River Cave at a lower level was substantially cooler. In the northern show caves, the average air temperature in the Diamond was slightly cooler than the Chifley and Imperial. On the basis of elevation, this result would not be expected, since the Diamond is higher than the Imperial. However connections to other passages (e.g. the Jubilee Cave) create complex airflows through the cave (J. James pers. com.), which may explain this discrepancy. More broadly, since the air temperature of a cave is frequently influenced by the surface temperature of the ground, it is plausible that variations in the microclimate of the surface karst (e.g. due to differences in aspect, exposed bedrock and vegetation cover) contributed to the difference in air temperature between the caves (Domínguez-Villar et al. 2013)

With the exception of the Temple of Baal, all of the caves exhibited seasonal variation in CO_2, with a summer maximum and a winter minimum. These trends are consistent with Australian (e.g. Smith 1998; Eberhard et al. 2003) and international (Spötl et al. 2005; Fernandez-Cortes et al. 2006; Liñán et al. 2008) literature which report that CO_2 concentrations typically peak in summer and decrease to a minimum in winter. Although changes in barometric pressure can cause air to flow into or out of a cave (Cigna 2004), external air temperature is a likely driver of seasonal variation in CO_2 at Jenolan. During winter, the cave atmosphere is generally substantially warmer than the external air, which increases air circulation as warm, moist air rises out of the cave and is replaced by comparatively cold, dry external air. Conversely, when external temperatures are warmer, a temperature inversion does not form and the comparatively cool, moist air remains within in the cave (Fernandez-Cortes et al. 2006). This presumption is in accordance with contemporary research by Waring and Hankin (2013), who found external air temperature is the key driver of air circulation in the Chifley Cave.

Furthermore, higher concentrations of CO_2 during summer are also likely, due to increased production of CO_2 by natural processes (Baker and Genty 1998). These include the diffusion of CO_2 from within epikarst air (rich in CO_2 from root respiration and the breakdown of organic matter), degassing from cave waters, and biological productivity in the cave (Fairchild and Baker 2012). Indeed contemporary research by Waring and Hankin (2013) has shown that on hot days, the airflow in the Chifley Cave causes soil-air that is rich in CO_2 to seep into the cave, particularly at Katies Bower.

In the Temple of Baal, the gradual accumulation of CO_2 during periods of high visitation, gradual decrease in CO_2 during periods of lower visitation and lack of seasonal variation was indicative of low ventilation during 2009-2012. This notion is consistent with the findings of Whittlestone et al. (2003), who reported low ventilation rates, such that the difference between the summer and winter concentrations of radon in the Temple of Baal was only "marginally discernable" (Whittlestone et al. 2003). The increases and decreases in CO_2 during periods of high and low visitation confirm that visitation is an important factor in the determining CO_2 levels within this cave and is consistent with the hypothesis of Michie (1997), that visitors to the Temple of Baal caused the high concentrations of CO_2.

Implications for management

The Chifley was the only cave where the concentration of CO_2 exceeded 5,000 ppm, the limit specified in Carbon Dioxide Exposure Standards (time weighted average), which allow a person to work an 8 hour day for 40 hours per week in 5,000 ppm of CO_2 (Safe Work Australia 2013). The same standards also specify a short term exposure limit of 30,000 ppm (3 %) CO_2 for a duration of 15 minutes. Although the maximum concentration of CO_2 exceeded 5,000 ppm in the Chifley, this was never for an extended period of time, as evident by the average daily concentration, which only once exceeded 4,500 ppm and never 5,000 ppm (Fig. 4). Consequently, it is extremely unlikely that the concentrations of CO_2 reported at any of the monitoring sites would have impacted the health or safety of visitors, cave guides, or maintenance staff.

Commercial cave tours frequently increased the air temperature and concentration of CO_2 within the cave atmosphere. In most of the caves these increases were relatively short lived and rapidly returned to the pre-tour level (i.e. fast relaxation time) immediately after the tour when visitation was moderate or at the end of the day during periods of high visitation. Consequently, in these caves, the current rates of visitation and tour schedules did not have any apparent lasting impact on the cave atmosphere. However the same was not true for the Temple of Baal, where the number of visitors influenced the concentration of CO_2 and resulted in an accumulation of CO_2 during periods of high visitation.

CO_2 is a crucial factor in many of the processes that form caves and their speleothems. An increase in the concentration of CO_2 in the cave atmosphere may initially impact active speleothems by decreasing the rate of calcite deposition and ultimately the dissolution of speleothems (James 2004). Kermode (1979) proposed that concentrations of CO_2 above 2,400 ppm result in aggressive water that can dissolve speleothems, and as a result, is the maximum permissible level in Glowworm Cave, New Zealand (de Freitas and Banbury 1999; de Freitas 2010), although the reliability of this threshold as a universal guideline has been questioned (e.g. Michie 1997; de Freitas and Banbury 1999). Recent research suggests that there is no universal threshold, but rather that the equilibrium of CO_2 between the air and water ultimately determines if calcite is deposited or dissolved (Baker and Genty 1998; Cigna 2002; James 2004). Moreover, research examining the influence of CO_2 on calcite deposition within the tourist caves at Jenolan found corrosion thresholds ranged from 2,690 ppm in the River Cave to 28,000 ppm in the Ribbon Cave and did not exceed the maximum CO_2 measured in the caves (Failes 1997). It is important to note that these thresholds do not apply to inactive speleothems and bedrock, and corrosive condensates that form as a result of increased concentrations of CO_2 from visitors can be highly damaging (James 2004, 2013), although fortunately many of the speleothems in the Temple of Baal appear to be active.

It is beyond the scope of the JEMP to measure and quantify corrosion thresholds of CO_2 within the caves and further research on the impacts of CO_2 on the caves is required, especially in the Temple of Baal. Specifically, measurement of the partial pressure of CO_2 (P_{CO_2}) of speleothem drip water and concentration of dissolved calcium could be used to accurately determine the sensitivity of speleothems to changes in the concentration of CO_2 in the cave atmosphere (Fairchild and Baker 2012). Nevertheless, in the Temple of Baal, visitation increased the concentration of CO_2 for lengthy periods of time, such that no seasonal variability was evident, and may in turn influence process such as the rates of calcite deposition. Furthermore, although the concentration of CO_2 in the Temple of Baal was below the limit specified by Safe Work Australia (2013), which allows a person to work an 8 hour day (40 hour week) in 5,000 ppm of CO_2, it has been suggested that visitors may experience discomfort from CO_2 concentrations < 2,500 ppm (Osborne 1981).

The most common methods of addressing issues of air quality in tourist caves are to limit visitor numbers and artificial ventilation (James 2004). Obviously if visitation causes an accumulation of CO_2 in a cave, a reduction in the number of people who visit that cave will lessen this accumulation. However, this is in direct conflict with commercial interests and is not a considered a realistic proposition. At the same time, given that visitors are elevating the concentration of CO_2 in the Temple of Baal, caution should be exercised when evaluating visitation rates and the possibility of increasing the number of people who visit the cave.

When considering the influence of visitation on the atmosphere and microclimate of Pozalagua Cave (Spain), Lario and Soler (2010) recommended closure of the cave one day per week during periods of "normal" visitation and two days per week after high visitation in order to minimise the cumulative effects of visitation. Given the low rates of ventilation and time taken for the concentration of CO_2 to decrease, it is unclear how successful a similar scenario would be in the Temple of Baal. Under the existing trends in visitation, the concentration of CO_2 gradually decreases with lower visitation following periods of peak visitation and accordingly, the environmental benefits of completely closing the cave would need to be weighed up against the economic benefits associated with visitation.

An alternative method of dealing with CO_2 is to ventilate the cave to prevent a build up of excessive CO_2. For example, careful manipulation of the airflow regimes is used to limit the accumulation of CO_2 in Glowworm Cave, New Zealand (de Freitas and Banbury 1999; de Freitas 2010; Gilles and de Freitas 2013). Similarly, Michie (1997) demonstrated that opening the airtight doors in the Binoomea Cut, an artificial tunnel that provides access to the Temple of Baal, can rapidly decrease the concentration of CO_2 in the cave atmosphere. However increased ventilation is likely to cause significant side effects that must be carefully considered. The maintenance of natural conditions is crucial to the conservation of a cave (Watson et al. 1997) and changes to the natural airflow frequently alter the microclimate of a cave (Gillieson 1996). Artificial ventilation often causes increased fluctuations in temperature and relative humidity (Russell and Maclean 2008) and is a major cause of desiccation of caves (Gillieson 1996; de Freitas 1997). Additionally, increased airflow circulates dust particles to a greater depth within the cave (Michie 2004) and is likely to discolour speleothems, thereby reducing their aesthetic value (James 2013). Consequently, any potential change to the air flow in a cave is potentially highly damaging and requires careful consideration (Michie 2004; Faimon et al. 2012).

The creation of artificial entrances modifies natural airflow, thereby altering the natural microclimate of a cave (Cigna 1993; Gillieson 1996). For this reason the International Show Cave Association (ISCA) states that "any new access into a cave must be fitted with an efficient system, such as double set of doors, to avoid creating changes in the air circulation" (ISCA 2010). The artificial entrance to the Temple of Baal, the Binoomea Cut, contains two air lock doors, which were installed after it was observed that the cave was drying out (J. James pers. com.). Prolonged opening of the airlock doors would undoubtedly increase airflow and decrease in CO_2, but is also likely result in the desiccation of the cave, especially in winter, when the artificial entrance may act as a "chimney" (see de Freitas and Banbury 1999 and Russell and Maclean 2008) as warm moist air is drawn out of the Binoomea Cut, while cold air is drawn in from the River Cave. This scenario would be highly undesirable, as the potential befits associated with decreased levels of CO_2 would almost certainly be outweighed by unnatural variation in the microclimate and desiccation of speleothems.

Previous studies have noted the conflict between maintaining a stable microclimate (in particular temperature and RH) versus the need for ventilation to manage the accumulation of CO_2 (e.g. de Freitas 1997; Michie 1999; Liñán et al. 2008). One solution to this conflict may be a compromise whereby limited ventilation is permitted through the Binoomea Cut. This could be achieved by temporary opening of the airtight doors (e.g. two hours as per Michie 1997), although this would be expected to increase the variation of air temperature and RH in the cave. Additionally, the manual opening and closing of the doors, may be problematic as it could be expected that the doors would accidently be left open from time to time, to the detriment of the cave. An alternative approach could be the installation of a window in each of the airlock doors that could be opened during peak visitation to allow limited airflow into the cave. A more limited airflow may allow the temperature and RH of the external air to partially equalise with the cave atmosphere before reaching the cave, whilst minimising the potentially harmful accumulation of CO_2.

As previously discussed, the circulation of air in caves is influenced by a number of factors including season and weather conditions. These factors may have significant implications for ventilation, since the influence of ventilation on the cave microclimate as well as its effectiveness in removing CO_2 can be highly variable depending on season and local weather conditions, and require different ventilation regimes (de Freitas 1997). With this in mind, any study of the effectiveness and impacts of ventilation must include temporal variation in airflow associated with season and varying weather conditions. Finally, in considering the possibility of increasing the ventilation in caves such as the Temple of Baal, it must stressed that any change to airflow within a cave requires careful consideration, and must be guided by ongoing monitoring, if long term impacts are to be minimised. Such considerations highlight the importance and value of long term, baseline data collected in environmental monitoring programs such as the Jenolan Environmental Monitoring Program.

Monitoring of the cave atmosphere at Jenolan provides valuable baseline data for the air temperature, relative humidity and concentration of CO_2 in the tourist caves. Regular measurement of these parameters has ascertained the caves are typically characterised by high levels of relative humidity, moderately stable air temperature with seasonal variation of < 2°C, and highly seasonal variation in concentration of CO_2. Commercial cave tours frequently increased the air temperature and concentration of CO_2, although both parameters rapidly returned to the pre-tour level after the tour had passed. An exception occurred in the Temple of Baal, where peak visitation elevated the concentration of CO_2 for extended periods of time, such that seasonal variation was not apparent.

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